

Workshop ‘Spatio-temporal modeling for ecology’

Stream network activity

Some (bibliographic) context

Fisheries Research 259 (2023) 106583



Contents lists available at ScienceDirect

Fisheries Research

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Catchment-scale stream network spatio-temporal models, applied to the freshwater stages of a diadromous fish species, longfin eel (*Anguilla dieffenbachii*)

Anthony R. Charsley^{a,*}, Arnaud Grüss^a, James T. Thorson^b, Merrill B. Rudd^c, Shannan K. Crow^d, Bruno David^e, Erica K. Williams^a, Simon D. Hoyle^f

Ecological Applications, 28(7), 2018, pp. 1782–1796
Published 2018. This article is a U.S. Government work and is in the public domain in the USA.

A geostatistical state-space model of animal densities for stream networks

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A geostatistical state-space model of animal densities for stream networks

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Overall framework

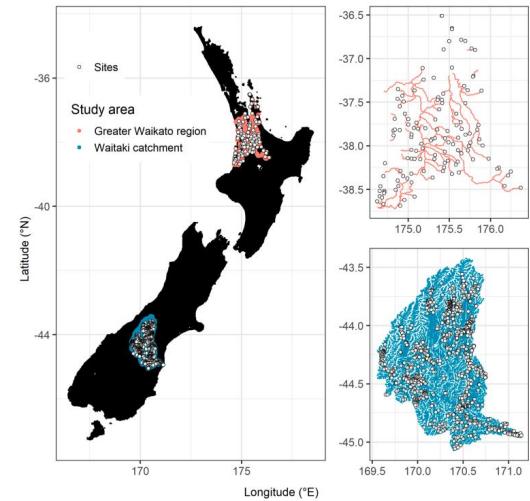
Case study: Longfin eel (*Anguilla dieffenbachii*), New Zealand

Ecological objective: estimating spatio-temporal changes in longfin eel populations in the freshwater environment

Data: Presence absence / Count data of eels, various fishing methods

- + Covariates (e.g. mean flow, distance to coast, mean elevation)

Statistical model: VAST + adaptation to stream network



Modeling framework | VAST

Linear predictor for observation i

$$p_1(i) = \mu_{\beta 1}(c_i) + \sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f) + \sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f) + \sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$$

Category (e.g. species)

Number of temporal effects

Number of spatial effects

Number of spatio-temporal effects

Temporal variation

Spatial variation

Spatio-temporal variation

+ $\sum_{p=1}^{n_p} \gamma_1(c_i, t_i, p) X(s_i, t_i, p) + \sum_{k=1}^{n_k} \lambda_1(k) Q(i, k)$

Habitat covariates

catchability covariates

Number of habitat covariates

Number of catchability covariates

Modeling framework | VAST

Linear predictor for observation i

$$p_1(i) = \mu_{\beta 1}(c_i) + \sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f) + \sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f) + \sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$$

Category (e.g. species)

Number of temporal effects

Number of spatial effects

Number of spatio-temporal effects

Temporal variation

Spatial variation

Spatio-temporal variation

Habitat covariates

catchability covariates

Number of habitat covariates

Number of catchability covariates

Temporal, spatial and spatio-temporal random effects

The diagram illustrates the VAST modeling framework. It starts with a linear predictor for observation i , $p_1(i)$, which includes a category effect ($\mu_{\beta 1}(c_i)$), temporal variation ($\sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f)$), spatial variation ($\sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f)$), and spatio-temporal variation ($\sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$). Below these are habitat covariates ($\sum_{p=1}^{n_p} \gamma_1(c_i, t_i, p) X(s_i, t_i, p)$) and catchability covariates ($\sum_{k=1}^{n_k} \lambda_1(k) Q(i, k)$). Arrows point from each term to its corresponding label. A bracket under the habitat covariates and catchability covariates is labeled 'Temporal, spatial and spatio-temporal random effects'.

Modeling framework | VAST

Linear predictor for observation i

$$p_1(i) = \mu_{\beta 1}(c_i) + \sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f) + \sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f) + \sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$$

Category (e.g. species)

Number of temporal effects

Number of spatial effects

Number of spatio-temporal effects

Temporal variation

Spatial variation

Spatio-temporal variation

Habitat covariates

catchability covariates

Number of habitat covariates

Number of catchability covariates

Loading terms

Relate the temporal, spatial and spatio-temporal effects to categories/species

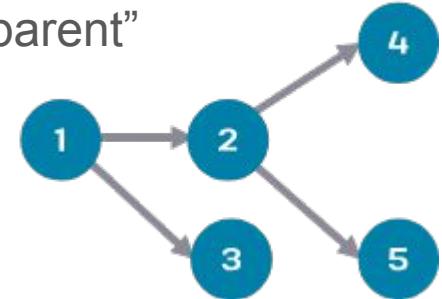
Temporal, spatial and spatio-temporal random effects

The diagram illustrates the VAST modeling framework. It starts with the linear predictor $p_1(i)$ and breaks it down into several components. At the top, three main components are shown: 'Temporal variation' (underlined), 'Spatial variation' (underlined), and 'Spatio-temporal variation' (underlined). Each of these underlined sections has a red dot above it, which points to a label: 'Number of temporal effects' (red), 'Number of spatial effects' (red), and 'Number of spatio-temporal effects' (red). Below these, the components are further detailed: 'Temporal variation' includes $\sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f)$ and $\sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f)$; 'Spatial variation' includes $\sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$; and 'Spatio-temporal variation' includes $\sum_{f=1}^{n_{\beta 1}} L_{\beta 1}(c_i, f) \beta_1(t_i, f)$, $\sum_{f=1}^{n_{\omega 1}} L_{\omega 1}(c_i, f) \omega_1(s_i, f)$, and $\sum_{f=1}^{n_{\epsilon 1}} L_{\epsilon 1}(c_i, f) \epsilon_1(s_i, f, t_i)$. Below these detailed components, there are two additional groups: 'Habitat covariates' ($\sum_{p=1}^{n_p} \gamma_1(c_i, t_i, p) X(s_i, t_i, p)$) and 'catchability covariates' ($\sum_{k=1}^{n_k} \lambda_1(k) Q(i, k)$). Each of these groups has a blue dot above it, which points to a label: 'Number of habitat covariates' (blue) and 'Number of catchability covariates' (blue). A large blue bracket at the bottom groups all these components together under the label 'Temporal, spatial and spatio-temporal random effects'. A red bracket on the right groups the 'Number of temporal effects', 'Number of spatial effects', and 'Number of spatio-temporal effects' under the label 'Loading terms'. A red text annotation 'Relate the temporal, spatial and spatio-temporal effects to categories/species' is located to the right of the 'Loading terms' label.

Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”



Modeling framework | Modelling spatio-temporal dependence

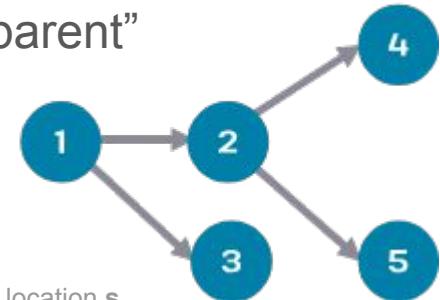
Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

$$\omega(s) | \omega(s_{\{parent\}}) \sim Normal(\rho_s(s) \times \omega(s_{\{parent\}}), \sigma_s^2(s))$$

Expected spatial correlation
between points in the stream network

Variance for spatial correlation for location s ,
conditioned upon the value for parent node s_{parent}



Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

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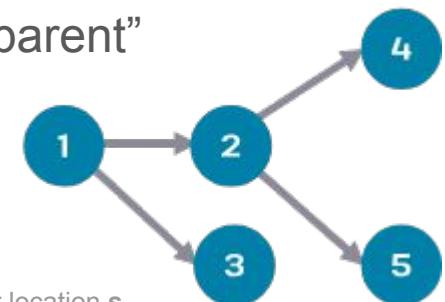
Variance for spatial correlation for location s ,
conditioned upon the value for parent node s_{parent}

$$\sigma_s^2(s) = \frac{\sigma_\tau^2}{2\theta_\tau} \left(1 - e^{-2\theta_\tau |s - s_{parent}|} \right)$$

Asymptotic variance for
two infinitely distant nodes

Exponential rate of decorrelations
between child and parent nodes,
⇒ Larger values represent faster decorrelation

Distance between location s
and parent node s_{parent}



Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

$$\omega(s) | \omega(s_{\{parent\}}) \sim Normal(\rho_s(s) \times \omega(s_{\{parent\}}), \sigma_s^2(s))$$

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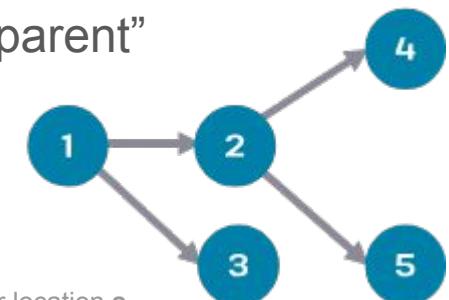
$$\rho_s(s) = e^{-\theta_\tau |s-s_{parent}|}$$

Variance for spatial correlation for location s ,
conditioned upon the value for parent node s_{parent}

$$\sigma_s^2(s) = \frac{\sigma_\tau^2}{2\theta_\tau} \left(1 - e^{-2\theta_\tau |s-s_{parent}|} \right)$$

Asymptotic variance for
two infinitely distant nodes

Exponential rate of decorrelations
between child and parent nodes,
⇒ Larger values represent faster decorrelation



Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

Then define the **precision matrix**:

$$Q_{\text{stream}}(s, s_{\text{parent}}) = Q_{\text{stream}}(s_{\text{parent}}, s) = \frac{-e^{-\theta_{\tau}|s-s_{\text{parent}}|}}{1-e^{-2\theta_{\tau}|s-s_{\text{parent}}|}}$$

*Precision \Rightarrow represents the **conditional dependence** of child nodes given parent nodes*

Exponential rate
of decorrelations

Distance between location s
and parent node s_{parent}

Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

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*Precision \Rightarrow represents the **conditional dependence** of child nodes given parent nodes*

Exponential rate
of decorrelations

Distance between location s
and parent node s_{parent}

Diagonal terms of
the precision matrix

$$Q_{\text{stream}}(s, s) = 1 + \sum_{s' \in S} \frac{e^{-2\theta_{\tau}|s-s'|}}{1-e^{-2\theta_{\tau}|s-s'|}}$$

Set of child and parent nodes
that are **adjacent** to node s

Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “stream “parent”

Then define the **precision matrix**

$$Q_{\text{stream}}(s, s_{\text{parent}}) = \frac{-e^{-\theta_{\tau}|s-s_{\text{parent}}|}}{1-e^{-2\theta_{\tau}|s-s_{\text{parent}}|}}$$

Precision \Rightarrow represents
conditional
dependence of child nodes given parent nodes

Diagonal terms of
the precision matrix

$$Q_{\text{stream}}(s, s) = 1 + \sum_{s' \in S} \frac{e^{-2\theta_{\tau}|s-s'|}}{1-e^{-2\theta_{\tau}|s-s'|}}$$

Exponential rate
of decorrelations

Distance between location s
and parent node s_{parent}

Set of child and parent nodes
that are adjacent to node s

Markovian properties

Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

Then define the **precision matrix**.

Extension to time through a first-order autocorrelation process (not described here).

Modeling framework | Modelling spatio-temporal dependence

Ornstein-Uhlenbeck process

Define the acyclic graph of upstream “child” and downstream “parent”

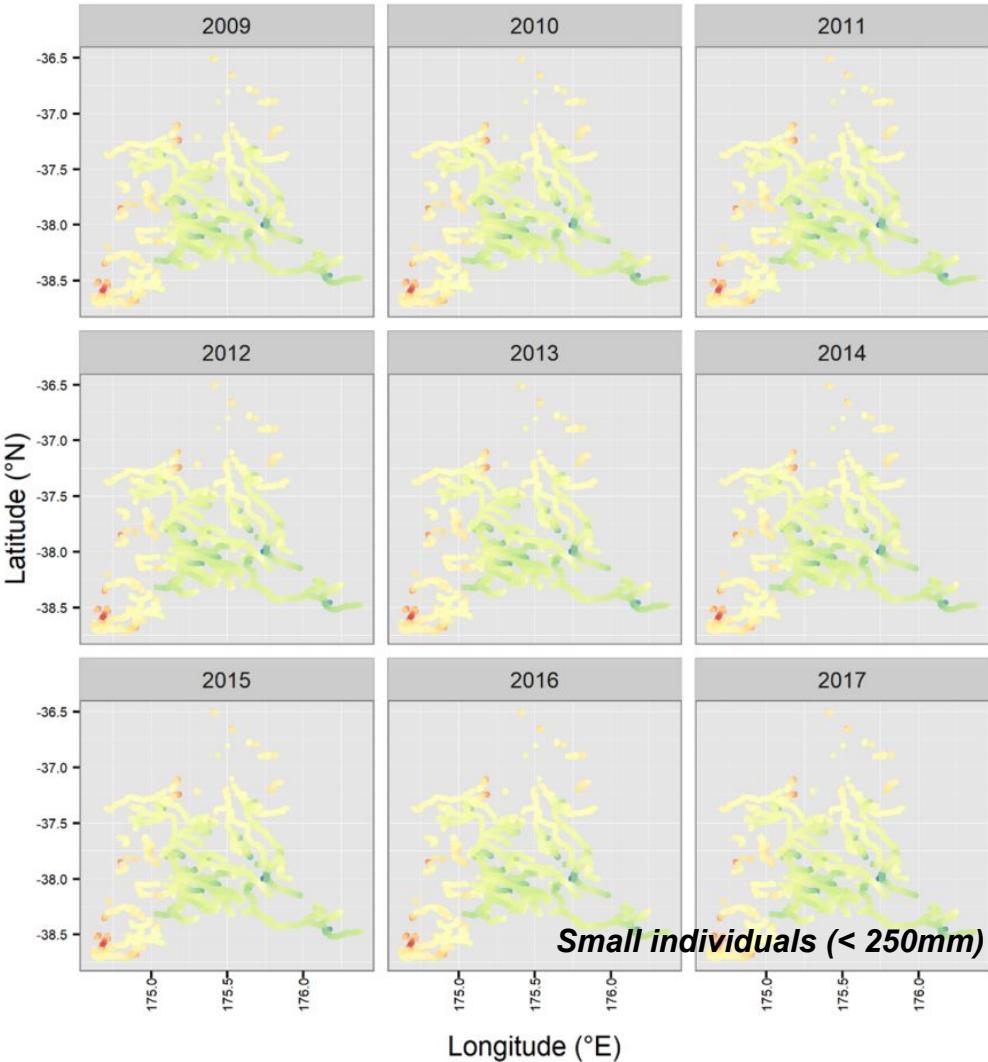
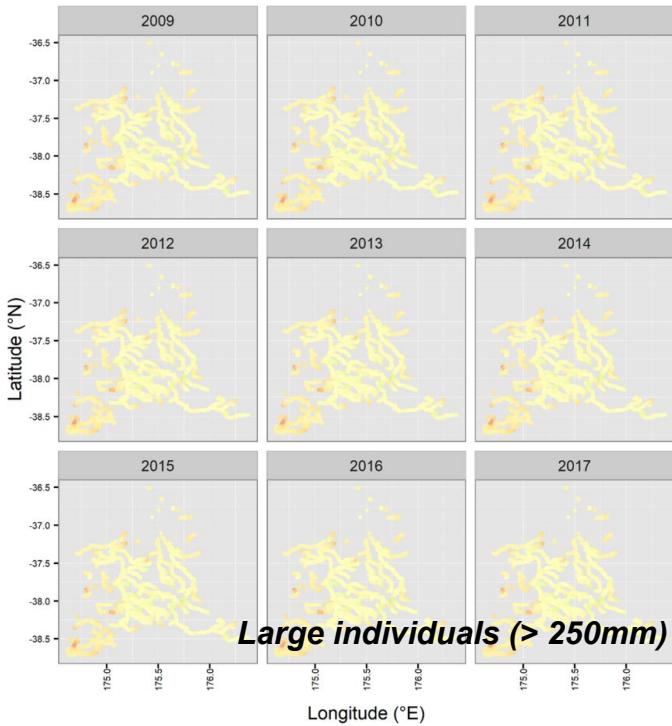
Then define the **precision matrix**.

Extension to time through a first-order autocorrelation process (not described here).

Inference realized with TMB (standard for VAST/tinyVAST).

Some results

Map of predicted count/km



Our case study

Case study: Freshwater fish in the Loire River basin
(France)

Ecological objective: Estimating spatio-temporal changes
in fish populations in the freshwater environment

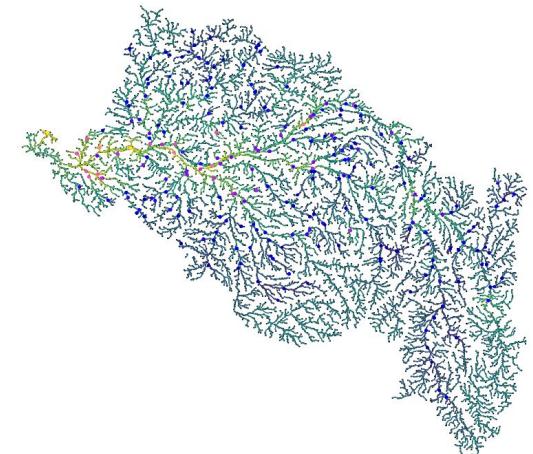
Data: Count data of freshwater fish in the Loire River
bassin, 1990-2024 (ASPE database, OFB)

- + Covariates (e.g. distance to coast, elevation)

Statistical model: tinyVAST with adaptation to stream
network



*European eel spatial distribution
in the Loire Bassin*



Codes and questions to address

https://github.com/balglave/stream_sdm.git

Adding environmental covariates → need an interpolation step for prediction

~~Adding additional species (e.g. TRFe) - truite ; SPI – spirlin ; CHE – chevesne ;~~

~~Checking the network~~

Other questions ?